NDT.net - January 2000, Vol. 5 No. 1

Emerging NDE Technologies and Challenges at the Beginning of the 3rd Millennium -- Part I, Part II

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Abstract

NDE is now a relatively mature field and, even though accurate characterization of hidden flaws may still pose a challenge, the last century of the second Millennium was marked with the most incredible progress. Practically, the majority of the current NDE methods were introduced around the middle of the twentieth century. Following modifications, improvements and enhancements contributed to an unprecedented advancement in capability and reliability of these methods and the emergence of new ones. As an interdisciplinary field, NDE benefited from capabilities that were developed in many other science and engineering fields. The resulting improvement touched every element of the NDE technology leading to smarter, smaller, lighter and significantly more capable instruments. The requirements for NDE are continuing to be driven by the need for lower cost methods and instruments with greater reliability, sensitivity, user friendliness and high operational speed. In addition to these needs, the technology is sought for applicability to increasingly complex materials and structures. The trend toward a global market led to a growing recognition of the value of international standards for test procedures and personnel qualification, where the documents issued by the International Standardization Organization (ISO) are becoming the leading ones. The NDE field is increasingly expanding to new frontiers as a result of defense budget cuts and shrinking in government funding of research and development. Moreover, structures are being designed to require less periodic inspection using no fundamentally new material, and there is a lower need for new methods to address such challenges as NDE of aging aircraft. As we begin the third Millennium, the author made an attempt to bookmark the status of NDE in this two-part. This part is focused on emerging NDE techniques that are mostly applicable to aerospace structures,

whereas the second part covers general technologies that benefited NDE and challenges to the field.

Introduction

The desire to NDE the quality and integrity of materials and structures has a very long history, where visual and tap testing have been the methods of choice since ancient times. The introduction of the Magnetic Particles and Liquid Penetrant methods marked the transition to sophistication of the NDE capability offering a superior sensitivity at greater reliability. Studies using various waves and forms of radiation that can travel through opaque material offered a series of candidates for employment as NDE methods. The greatest progress was observed when effective data acquisition and display capabilities were developed to extract and record information about discontinuities and material properties. Around the middle of the twentieth Century, practical instruments that rely on electromagnetic and elastic waves at various wavelengths have emerged [McMaster, 1963]. Fundamentally, these methods were involved with the evaluation of reflected and/or transmitted waves after interacting with the test part. The earlier methods have been Eddy Current and Radiography and were followed by Ultrasonics, Thermography and Holography. Later, Acoustic Emission, Magnetic Resonance Imaging (MRI) and Shearography have emerged during the Seventies. In the absence of effective analytical tools prior to the Eighties, the data interpretation depended strongly on the experience and expertise of NDE personnel. In search for new capabilities, investigators sought correlation between various material variables and physical measurements. Some of the successful results are still being applied, including the assessment of thermal treatment and hardness of metallic parts using eddy currents to determine the relative conductivity.

One of the main objectives of the early studies has been to determine the strength of materials and bonded joints. Soon, it was recognized that while information about the integrity and stiffness can be extracted directly from NDE measurements, strength and durability cannot be measured by NDE methods because these are statistical and not physical properties. At the early 70's, in an effort to establish sound foundations for NDE using theoretical models and analytical techniques, DARPA started funding research and development studies of quantitative NDE. Since that time, under the Air Force Materials Lab sponsorship, conferences have held annually reviewing the progress in quantitative NDE. These conferences helped fostering and strengthening technical collaborations and provided a forum for reporting the scientific and engineering progress. Advancement in computers, electronics, and improved analytical techniques led to transitioning NDE from qualitative to more quantitative field. Finite element models are used to investigate the effect of flaws and structural geometry on the wave behavior and the measured response. Also, inversion techniques were developed to determine flaw characteristics and material properties. As a result, increasingly minute flaws can be detected at a higher probability and repeatability with less reliance on inspector capability, thus minimizing human errors.

In addition to the integration of technologies from other fields, there has been in recent years, the use of NDE methodologies and noninvasive techniques have been transition to other areas, including medical diagnostics, mine detection, meat and agriculture, geophysics, infrastructure [Boro & Reis, 1998], remote inspection, microelectronics, micro-electro-mechanical systems (MEMS), automation, etc. Using sensors and real time monitoring allows inspecting parts and structures at speeds of production lines and train ride while testing the rails. In recognition of the potential benefit of synergistic interaction with other sciences and technologies, recent

ASNT conferences have been increasingly including Sessions on interdisciplinary topics. Robotics, medical diagnostics and treatment, technology transfer, miniaturization and others are increasingly becoming common Session topics of the semi-annual ASNT conferences and the Annual ASNT Research Symposia. The NDE research community is continuing to have the objective to improve the capability of inspection methods to reliability detect critical flaws at lower cost with minimum impact on the serviceability and life cycle of the test structure. The topic of emerging technologies and challenges is very broad, and it is very difficult to thoroughly cover it in a single paper. The focus of this paper is on the application to NDE of aerospace structures.

Accepting the reality that no single method can provide all the necessary NDE information, efforts are being made to integrate several methods. The complimenting capabilities offer greater detectability and the overlapping ones enhance the reliability. Data fusion techniques [Gros, 1996] are being developed to allow effective data-acquisition and processing as well as provide a sound interpretation of the test parameters in relation to the material integrity. Instruments are now commercially available that can be used to perform ultrasonic and eddy current tests using the same core hardware with interchangeable transducers and modules. Also, to support such systems capability, commercial software packages are available to process data obtained from various NDE methods. Once data is acquired, the image can be analyzed and manipulated using a common set of software features providing greater user friendliness of the systems. The increased processing speed and improvement in hardware is allowing real-time imaging of all the wave-base NDE methods including radiography, ultrasonics, shearography, etc. Using analytical tools, finite element analysis as well as computer hardware and software, test procedures can be developed graphically by interactive process simulation. Moreover, progress in microelectronics led to the development of pocket size instruments.

As we begin the third millennium, a large arsenal of NDE techniques is available with superb capabilities and speed. It is interesting to review the leading methods and provide a snapshot of the capability of these methods at this point in the history of NDE. The specific methods that will be covered include visual, eddy current, radiography, ultrasonics, radiography, shearography and thermography. Due to page limits subjected on papers the other methods, such as tap testing, and acoustic emission, are not covered herein.

Visual

Visual inspection is continuing to be the leading NDE method and it represents the highest percentage of the inspection procedures that are applied to aircraft in service. To enhance the inspection capability, new tools were developed including improved illumination techniques, miniature video and dexterous small-diameter boroscopes. In recent years, two visual inspection techniques have emerged that worth noting and they are the D-Sight and the Edge of Light (EOL). While D-Sight already found its way to practical use, the EOL technique is relatively new and it is still in development stages.

Dual-Pass Light Reflection (D-Sight ᵀᴹ)

Surface and near-surface flaws, such as corrosion in metals and impact damage in composites, are causing a local surface deformation. The visual inspection technique called D-Sight (Diffracto Limited) [http://www.diffracto.com/products/dsight/dsight.htm] enhances the appearance of this deformation and increases its visibility [Forsyth, et al, 1998]. A D-Sight

inspection system consists of a CCD camera, a white light source mounted slightly above the camera lens, and a retro-reflective screen. In Figure 1, a schematic view is showing the principle of D-sight operation and on the right an example of cold worked holes is shown. The system's screen is made of a reflective micro-bead layer and is the most important element of the D-Sight system. While the screen returns most of the light in the same direction of the incidence, a slight amount of light is dispersed. When a surface is illuminated by a light source, local surface curvatures are focusing or dispersing the light onto the retro-reflective screen. A light pattern is formed on the screen and is reflected back to the source with a slight dispersion. This path of the light is backlighting the part surface and enhances the scattering effect of surface deformations. By viewing the surface slightly off-axis from the light source a unique pattern appears near local surface deformations. This pattern consists of bright and dark gray scale variations, where higher curvatures appear more intense due to the effect of focusing and diffusing the light. To obtain a sufficient level of diffused light the surface must be reflective, otherwise a thin layer of liquid needs to cover the surface to increase its reflectivity.

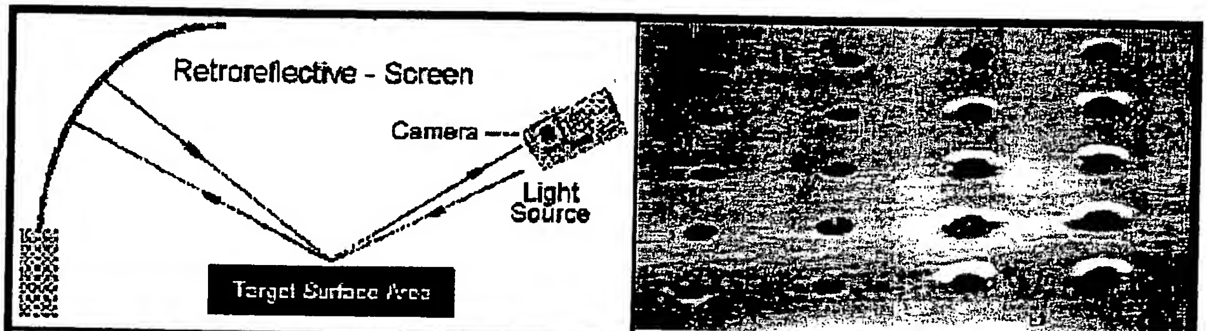
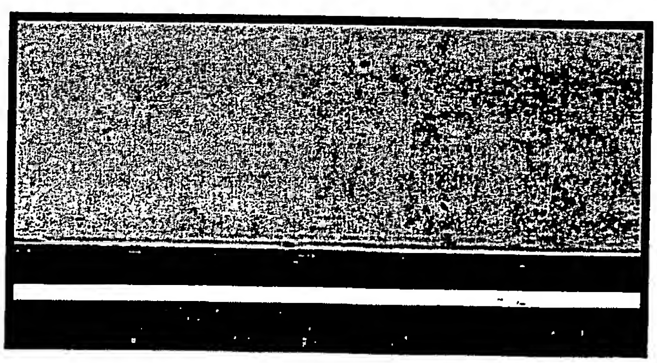


Fig 1: D-Sight principle of operation (left) and an example of cold worked holes (Diffracto Limited)

Edge Of Light ^{TM} (EOL)

Another method of enhancing the surface deformation that is caused by flaws is the Edge of Light^{TM} (EOL), which was developed by the National Research Council Canada [Forsyth, et al, 1998]. It employs elements commonly used in optical scanners and it uses the scattered light from surface deformation and variations in the surface slope to produce an image that consists of light intensity variations. The technique is relatively quick, with scanning speeds on the order of 2 to 20-linear cm/sec with line scan widths of 10-cm or more. EOL inspection results are easy to interpret since they closely resemble the actual subject. The technique has been demonstrated to be effective in detecting corrosion on surfaces and joints, as well as flaws in gas turbine components and turbine disks. For some applications, EOL was shown to have greater detection capability than liquid penetrant, magnetic particle, ultrasonic inspections, or optical microscopy. In Figure 2, a comparison is shown between an unaided view and EOL image of corrosion pillowing in a lap-splice joint of a Boeing 727 aircraft.



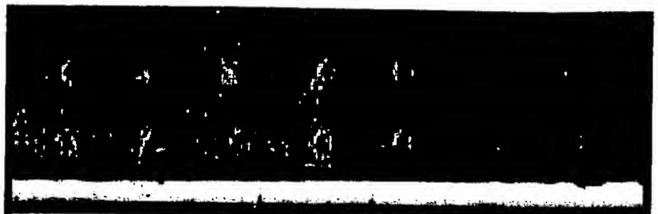


Fig 2: Top - Lap splice joint from a Boeing 727, as seen by the unaided eye
Bottom - EOL image of the same joint clearly showing corrosion pillowing

Eddy Current

For over four decades, eddy current has been one of the leading in-service inspection methods for crack detection around and inside fastener holes. Significant improvement has been made to enhance the method capability, reliability and user friendliness. The modeling of the effect of flaws contributed significantly to the understanding of the key parameters as well as the reduction in the effect of noise and liftoff. Improved probes and instrumentation were developed and the effective use of low frequencies enabled inspection of metallic layered structures for detection of flaws in the second and third layer. The Magneto-Optics Imager (MOI) has been one of the spin-offs of the eddy current technique and it is becoming increasingly a practical method for aircraft testing. Another eddy current technique that has emerged in recent years is the pulse eddy current. The early phases of the development of this technique were made at Iowa State University and South West Research Institute and currently it is being transitioned to a practical hardware at the Canadian National Research Council. Further, to detect cracks in thick or multilayered metallic structures, the method called SQUID was developed.

Magneto-Optics Imager (MOI)

In order to simplify the detection of flaws, the Magneto-Optics Imager (MOI) was developed as a means of visualizing the eddy current response [Fitzpatrick, et al, 1996]. The Magneto-Optic Imager (MOI) combines planar eddy current and magneto optic imaging and it is applicable to inspection of metallic structures for surface and subsurface flaws. MOI allows real time imaging through paint and other surface coverings where the results are projected either on a heads up display or a monitor. MOI is employed in a hand-held (see Figure 3) portable instrument that requires minimal training and its capability greatly increases the speed and reliability of inspection. This method is increasingly being used for aircraft inspection by airlines, maintenance facilities and the military.

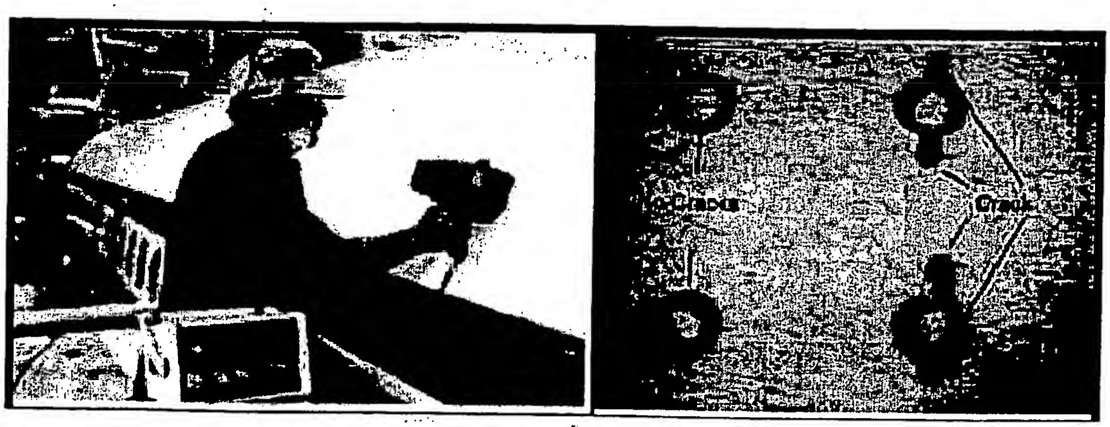


Fig 3: A photographic view of an MOI inspection (left) and an image of indication of cracks around fasteners (right) (PRI, Torrance, CA)

Pulsed Eddy Current (PEC)

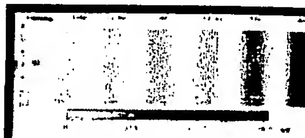


Fig 4: PEC amplitude C-scan of 2-layer plate specimen with metal loss located at the top of the second layer

Conventional eddy current techniques use single frequency sinusoidal excitation and measure flaw responses as impedance or voltage changes on an impedance plane display. To detect flaws, inspectors interpret the magnitude and phase changes, however the method is sensitive to variety of parameters that are hampering the characterization of flaws. Multiple frequency measurements can be combined to more accurately assess the integrity of structures by reducing signal anomalies that may otherwise mask the flaws. Initial development led to the use of dual frequency eddy-current where frequency-mixing functions allowed the quick application of the technique. This approach has been shown to be useful in reducing the effects of plate separation variations when inspecting for second layer corrosion in lap splices [Thompson, 1993]. The dual frequency method offers advantageous when performing large area inspections by means of eddy current C-scans of specimens with corrosion under fasteners [Lepine, et al, 1998]. Unfortunately, conventional multiple frequency methods can provide limited quantitative data and are difficult to use for flaw visualisation in an intuitive manner. Swept frequency measurements using impedance analysers perform well in quantitative corrosion characterisation studies, especially when they are interpreted in conjunction with theoretical models. However, the application of these techniques is too laborious. In contrast to the conventional eddy current method, pulsed eddy current (PEC) excites the probe's driving coil with a repetitive broadband pulse, such as a square wave. The resulting transient current through the coil induces transient eddy currents in the test piece, which are associated with highly attenuated magnetic pulses propagating through the material. At each probe location, a series of voltage-time data pairs are produced as the induced field decays, analogous to ultrasonic inspection data. Since the produced pulses consist of a broad frequency spectrum, the reflected signal contains flaw depth information. Physically, the pulse is broadened and delayed as it travels deeper into the highly dispersive material. Therefore, flaws or other anomalies close to the surface affect the eddy current response earlier in time than deep flaws. Similar to ultrasonic methods, the modes of presentation of PEC data can include A-, B- and C-scans. Interpretation, therefore, may be considered more intuitive than conventional eddy current data. The excitation pulse, signal gain and sensor configurations can be modified to suit particular applications. Examples of C-scan results of testing two plat layers with various degrees of thickness loss on the top of the second layer are shown in Figure 4.

Superconducting Quantum Interference Device (SQUID)

SQUID is a magnetic field sensor for eddy current measurements that are highly sensitive even at low frequencies. SQUID has very high magnetic field sensitivity, which is nearly independent of frequency, allowing inspection of large depths using low frequencies. The technique was demonstrated to be highly effective in flaw detection however in its current state it requires cooling to cryogenic levels. Recent research [e.g., Kreutzbruck, 1998] has shown a superiority of SQUID over conventional eddy current systems when searching for cracks at depth of 10 mm or more. Further, it was shown to have an improved signal to noise ratio of up to 3 orders of magnitude for cracks deeper than 13mm. Additionally, the high bandwidth available with certain SQUID systems makes measurements over a wide frequency range possible without having to change the sensor. The high dynamic range (the ratio between the highest field change which can be measured before the system goes into saturation and the

lowest detectable field) allows one to detect small field changes in the presence of large background fields, produced e.g. by edge effects or inhomogeneities in conductivity. The method is effective mostly in low frequency applications for the detection of deep lying defects, in multilayer structures, rivet plates and aircraft wheels. One concern that needs to be taken into account is that for deep structures the eddy currents spread over a larger area and the spatial resolution might be too low for practical purposes. The large dynamic range of SQUID allows shorter integration time and therefore faster scanning is possible. Depending on the conductivity variation of the tested plates a substantial background might occur, which limits the reliable detection of deep lying and small cracks.

Radiography

The capability of radiography to provide an image that is relatively easy to interpret made it an attractive NDE method for both industrial and medical applications. The health hazard associated with the exposure to this ionizing radiation and the use of films to record the images constrained the application of radiography. The development of real time imaging techniques for radiographic visualization helped overcoming the time consuming process that was involved with film recording. Moreover, computer processing of digitized images enabled the enhancement of the images as well as the quantification of the inspection criteria. Several radiographic techniques that deserve attention include the CT scan, Reverse Geometry X-ray and Microfocus X-ray microscopy. .

Compute Tomography Scan

Computer processing of the distribution of the X-ray transmission coefficient in a structure using a series of viewing angles is used to produce computed tomography (CT) scans [Kak and Slaney, 1988]. For over three decades, this radiographic technique has been widely in use as an important medical tool. At the early 80's the technique was transferred to industrial use as a result of a research effort at the Air Force Materials Laboratory. The method is highly effective in testing composite structures and it provides a quantitative information about the distribution of the material density. Images can be produced and manipulated in a real-time format and allow recognition, localization and classification of material defects (e.g. pores, blowholes, foreign bodies). The inspection can be done automatically in arbitrary test samples (e.g. in metal, ceramic, glass or synthetic material castings). Three-dimensional position and extension of flaws can be determined by evaluating pairs of stereoscopic transmission images [Chen, et al, 1990]. Depending on the object geometry, the acquisition of stereoscopic images can be done alternatively by translation or rotation of the sample. The defect extension in the direction of transmission is calculated by using the absorption law adapted for polychromatic radiation. An example of a graphite/epoxy sample tested by CT scanning is shown in Figure 5.

Reverse Geometry X-Ray (RGX) Imaging

In contrast to conventional radiography, RGX reverses the relative sizes of source and detector as well as the location of the object [Dolan, et.al, 1993]. The object is placed adjacent to the large, computer controlled raster-scanning source at a distance from the point detector. This arrangement allows scattered radiation to bypass the detector, thereby increasing the contrast sensitivity (signal-to-noise ratio). The method has been demonstrated to detect such flaws as corrosion, impact damage, and water entrapment in aluminum and composites. In the case of corrosion on aircraft, it was possible to detect the loss of material down to as little as 1.0 even when the material loss is disguised by the presence of corrosion products. An example of a Reverse Geometry test of corrosion on a horizontal stabilizer of an F-111 aircraft is shown in

Figure 6. Generally, the distance between object and detector can be easily increased to reduce parallax effects and increase throughput for large area honeycomb and/or thick honeycomb inspection.

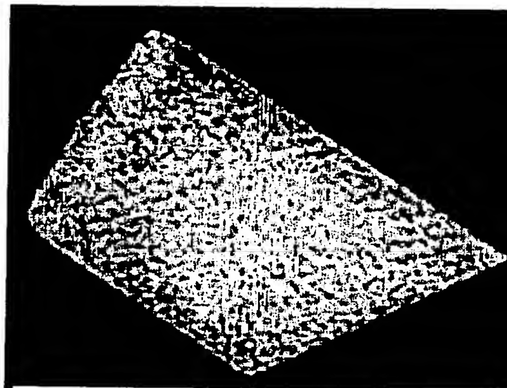


Fig 5: CT image of the density distribution in a reference graphite/epoxy sample

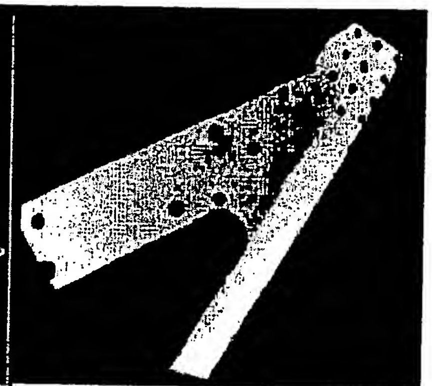


Fig 6: Reverse Geometry image of corrosion on a horizontal stabilizer of an F-111 aircraft (Digiray)

Microfocus X-ray Microscopy

Using a small source to provide a great magnification of the inspected object, Microfocus X-ray Microscopy operates similarly to conventional radiographic techniques [Olivas, et al, 1997]. Conventional radiographic techniques generate X-rays from a thick target, typically tungsten, oriented at 30^{o} or 45^{o} angles to the electron beam source. X-ray images are produced with limited magnification. Through the use of a thin film target oriented normal to the electron beam source, samples are positioned opposite to the beryllium window thereby minimizing working distance and maximizing magnification. The microfocused beam (~3μm) further enhances the resolution by increasing sharpness of the image as compared to the one obtained using larger focal spot sizes. Geometric magnification for typical fine-focus applications are ranging from 3X to 1000X with capabilities of extending beyond 2000X. For conventional transmission microfocus X-ray, the tube voltage ranges from 10 - 225kV with focal dimensions from 3 to 200μ m. By manipulating the sample and viewing a real-time image, defects normally obscured by background noise in conventional 2-D can be readily imaged. The technique is widely used for NDE of microelectronics and aerospace applications for parts with miniature internal components. An example of images obtained using Microfocus X-ray from two different viewing angles are shown in Figure 7, where a hydrophone with a microns size tunneling tip was examined.

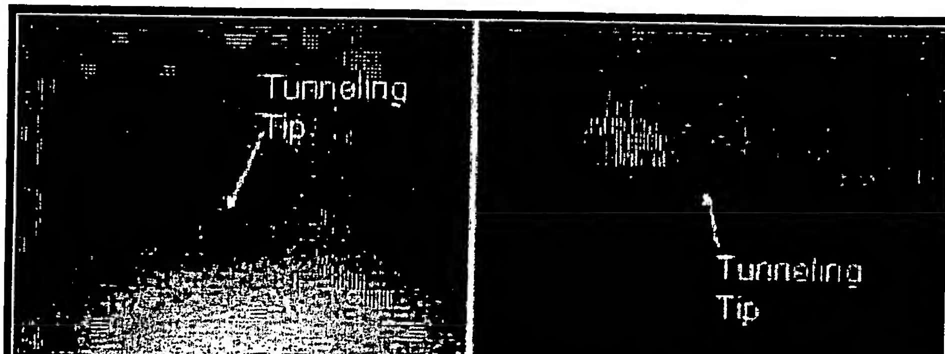


Fig 7: Microfocus X-ray image of a hydrophone tunneling tip as viewed from isometric (left) and profile (right) views

Ultrasonics

Ultrasonics is one of the most versatile and informative NDE methods and [Bar-Cohen, 1990]. The various modes that these waves can support allow the extractions of detailed information about flaws as well as determining various material properties. Techniques were developed employing the various wave modes as well as scattering and mode-conversion that are associate with the wave interaction. Examples of such techniques include the Acousto-Ultrasonics, which is practically used for flaw screening, and the ultrasonic angular insonification to induce the polar backscattering and leaky Lamb waves. Also, to perform rapid inspection portable scanners were developed with some that can crawl on the surface of the test structures and conduct scanning. To simplify the imaging process without the use of mechanical scanning array transducers and CCD technology can now be used to form the ultrasonic equivalence of the video cameras. The difficulties associated with the need for liquid couplant, which mostly affects field application, led to the development of various fixtures including water filled boots and wheels, bubblers and squirters. Recently, a dripless bubbler was developed at Iowa State University where water is recycled using a vacuum pump [Patton and Hsu, 1998]. Even though the bubbler adds significant mass to the probe mount, it maintains most of the water and it was demonstrated as an effective method of performing the equivalent of immersion in field conditions. Alternative dry coupling methods were also developed including the use of air- coupled piezoelectric transducers, Electro-Magnetic Transducers (EMAT) and Laser Ultrasonics [Green, 1997].

Dry Coupling Techniques

The inability to transmit and receive ultrasonic waves through air or gas was a limiting factor in developing rapid field inspection, testing porous or water sensitive materials, and others. Most ultrasonic NDE applications operate at frequencies in the range of 1- 10 MHz, where traveling through air is highly attenuative. The acoustic impedance of air differs significantly from the one for the piezoelectric transmitter and the test part causing reflection of most of the energy. Therefore, only a very small fraction of the energy is transmitted through the part and back to the transducer.

Air-Coupled transducers

One solution to overcoming this air-coupling problem without using additional transition media has been the induction of sufficiently high sound level and using high-gain, low-noise amplification [Grandia & Fortunko, 1995]. To enhance the transmitted energy, the transducer is used with no backing layers and thus taking advantage of the high mechanical-quality factor Q of piezoelectric disks. To improve the generation and reception efficiencies of the transducer, its front protection layer is made of a thin porous material having low specific impedance. The transducer is driven by tone-bursts with a center frequency that exactly matches its thickness- mode resonance and using focused transducers further increases the sound pressure. Such transducer and hardware modifications allowed the operation of air-coupled ultrasonic C-scans at frequencies in the low Megahertz range.

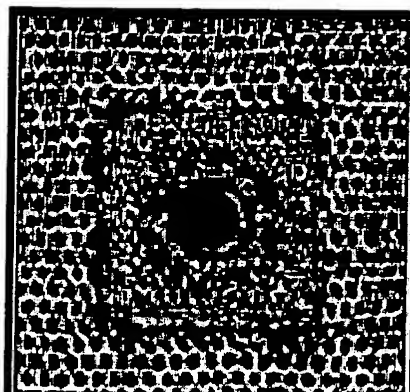


Fig 8: A 400 KHz air-coupled through-transmission C- scan of solar honeycomb panel with a 5x5-cm stiffener insert

While it is still limited to materials with relatively low acoustic impedance, such as composites,

it is already being used extensively for applications where water can not be used as a couplant. In Figure 8, an example of a C-scan is shown where a solar honeycomb panel with a 5x5-cm stiffener insert was tested using a 400 KHz air-coupled through-transmission. The bonded honeycomb core, the area of the insert and the missing core can be easily seen.

Electromagnetic acoustic transducer (EMAT)

EMAT is a transducer that uses eddy current to generate and receive acoustic signals that operates without a coupling medium [Oursler & Wagner, 1995]. The transducer can induce specific ultrasonic modes including normal beam and angle-beam shear wave, Shear Horizontal (SH) plate wave, Rayleigh wave and Lamb wave. The ability to induce horizontally polarized shear waves has a great significance for the inspection of austenitic welds. Another advantage of EMAT is the ability to operate at high temperatures. The main disadvantage of EMAT arises from its relatively low transmitted ultrasonic energy causing electronic noise to constrain its dynamic range. Also, the induced energy is critically dependent of the probe proximity to the test object, which for practical applications it is commonly maintained below 1-mm. Generally, EMAT transducers are used at frequencies below 2-4MHz.

Laser induced ultrasound

Laser ultrasonics is one of the effective methods of inducing and receiving ultrasonic waves without the need for couplant. The received signals are evaluated very similar to the pulse-echo technique and parts can easily be scanned from a distance of about 3-4 meters. The method induces short pulses in the range of 10-μsec causing a rapid heating and expansion of the surface forming elastic pulses. The reflected signals are examined by interferometry and such systems were developed by several research organization including the Center for NDE at John Hopkins University, Hughes Research Lab and the Canadian National Research Council [e.g., Monchalin, et al, 1998]. Also, a commercial system was developed by UltraOptec (Québec, Canada), who delivered one of its products to the Air Force maintenance facility at McClellan Air Force Base for inspection of composite and bonded structures [Fiedler, et al, 1997]. The method is effective for inspection of structures with complex geometry allowing examination of surfaces with a slope of up to about $\pm 45^{o}$. This allows mapping defects in parts that are contoured and presenting the results in 3-D (see Figure 9) with is no critical orientations requirement for the incident beam. The limiting factor in the scanning speed is the inability to induce pulses at high rate, where an average of 100 pulses/sec is commonly used. Overall, the cost and the sensitivity of the laser ultrasonic technique are limiting the wide usage of laser-ultrasonics. New techniques are continuously being introduced in an effort to reduce the cost of the hardware. However, the sensitivity is fundamentally limited to about 45dB because there is a lower bound on the sensitivity of detecting a single phonon, whereas the upper limit is set by thermal damage prevention. Commercially available systems are offering user friendly imaging software, which displays A-scans, B-scans and C-scans, as well as 3-D ultrasonic images that can be easily manipulated for various angles of view.

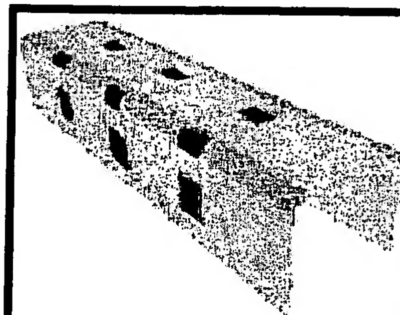
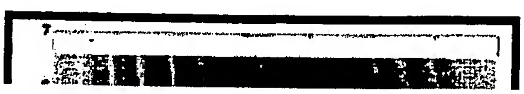


Fig 9: A 3-D C-scan image of a curved part with flaws at various depth (identified in colors) using laser-ultrasonic time-of-flight

Oblique Insonification NDE of Composites

Composite materials are now making a significant percentage of aircraft and spacecraft flaw critical



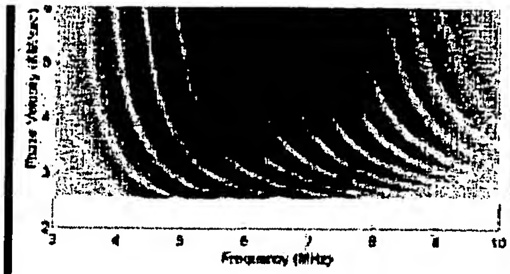


Fig 10: A new method of acquiring dispersion data, developed at JPL, allows recording very low amplitude modes

structures. These materials susceptibility to flaws during production and assembly as well as the cost associated with their inspection are hampering their wide use. These materials are now reaching service duration for which flaws due to aging are requiring a greater attention. Standard NDE methods developed to inspect metallic structures were adapted by the industry for inspection of composites partially accounting for their multi-layered anisotropic nature. The adapted methods are providing limited and mostly qualitative information about the material properties and defects. The author discovery of the ultrasonic Polar Back-Scattering (PBS) [Bar-Cohen & Crane, 1982] and the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1994] phenomena (1979 and 1982, respectively) in composites added a powerful arsenal of quantitative NDE methods. These phenomena are based on obliquely insonified ultrasonic waves and the numerous analytical and experimental studies followed the discovery of these phenomena are helping to pave the way for their practical application. Using PBS, the fiber orientations can be determined and porosity clusters as well as fatigue cracks can be mapped. Further, using inversion of LLW data, the elastic properties of composite panels can be determined, flaws can be characterized uniquely, and the quality of adhesive bonded-joints can be determined [Bar-Cohen, et al, 1993 and Bar-Cohen & Lih 2000]. The LLW data is acquired in the form of dispersion curves that show the phase velocity as a function of the frequency along various polar angles with the fibers. To harness the capabilities that are offered by LLW and PBS, a computer-controlled scanner was developed jointly with QMI (Costa Mesa, CA) as a C-scan attachment. Recent modifications of the data acquisition capability increased the speed of acquiring dispersion curves to fractions of a minute. Rapid acquisition of dispersion curves is very important for the practical implementation of quantitative mapping of the material properties. In addition a new capability was introduced using frequency modulation allowing to record very low amplitude LLW modes as shown in Figure 10.

Portable Real-Time Imager Using CCD

Ultrasonic imaging using a portable real time system that employs 2-D sensing array has been shown to be effective field inspection tool [Lasser & Harrison, 1997]. An ultrasonic camera displays images at TV frame rates and this capability contrasts the conventional C-scan, which generates image by point-by-point scanning of test areas. This real-time imager offers a portable, practical tool for rapid visualization of flaws using an integrated circuit, which converts ultrasound data to standard TV output. The system operates as a pulse-echo tester and it is designed to display different depth views by examining various time-of-flight ranges. The inspector applies an ultrasonic couplant over the desired test area and then presses the imager against the target insonifying it ultrasonic waves. The pulse-echo image appears on a small LCD screen mounted on the back of the probe. Controls are located on the handle facing the user and real-time adjustments can be made to select the desired characteristics of the image.

Shearography

The ability of holography to produce flaw indications that are superpositioned onto a 3-D image of parts were highly attractive features that were well documented since the 60's. The process involves double exposure of the structure at two different stressing

levels. Unfortunately, the method is very sensitive to the setup vibrations or displacement making it unpractical. The introduction of shearography to form double exposure without concern to the mechanical stability was a turning point for the technique. A digital interferometry system is used to detect areas of stress concentration caused by material anomalies [Maji, 1997]. The technique senses out-of-plane surface displacements in response to an applied load. Data is presented in the form of a fringe pattern produced by comparing two states of the test sample, one before and the other after a load is applied. Electronic shearography incorporates a CCD camera and frame grabber for image acquisition at video frame rates. Fringe patterns are produced by real time digital subtraction of the deformed object image from the reference object image. Shearography also uses a 'common-path' optical arrangement, which provides reasonable immunity to environmental disturbances such as room vibrations and thermal air currents. As a result, shearography can be implemented without the need for sophisticated vibration isolation that is required for conventional holography. The capability of Shearography to inspect large areas in real time has significant advantages for many industrial applications including inspection of composite structures and pressure vessels. Experience in testing bonded composites and metallic assemblies at Northrop Grumman Corp. since 1988 showed 75% reduction in inspection time compared to other NDE methods. Further, there are many cases where this method was found to be the only one capable of detecting the specific flaws.

Fig 11a: Tripod mounted shearography camera/laser is shown inspecting an aircraft (Laser Technology, Inc.)

Fig 11b: The bull's eyes shape of flaws' shearographic image

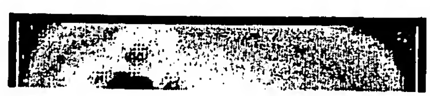
To address the requirement to stress the test structure, various techniques are used, where the most effective are thermal and surface vacuum techniques. The thermal shearography is used to inspect near skin-to-core bondline, ramp areas and solid graphite laminates, whereas, vacuum stress shearography is used to examine both near and far side bond lines in the honeycomb areas. Thermal stress shearography has been shown to be capable of inspecting large areas of composite and honeycomb materials at a rate of 60-ft^2 /hour [Davis, 1996]. Example of testing an aircraft is shown in Figure 11a and a typical view of flaws is shown in Figure 11b. Generally, due to the method of forming shearographic images flaws tend to appear as bull's eyes.

Thermography

The effect of flaws on the thermal conductivity and emissivity of test materials is analyzed by the thermographic NDE method [Jones & Berger, 1992]. Its attractive features are the capability to cover large areas in a single frame and it does not require coupling. Unfortunately, this method was found unreliable when testing bonded joints with a narrow gap between the unbonded surfaces. In the early stages, liquid crystals were used to map the temperature distribution on the surface. Improvements in infrared systems led to highly sensitive and effective tools for mapping the cooling or heating profiles and rapidly indicating flaws. Examining the temporal gradient of the thermal maps, i.e., thermal flux, significantly improved the detectability of flaws.

Thermal Wave Imaging

Thermal waves transmitted through test parts can be received and used to produce an image of the internal uniformity. In



addition to imaging the pattern of subsurface flaws and corrosion, the technique can rapidly (few seconds) provide quantitative measurements of less than 1% material loss [Favro & Thomas, 1995]. As heat source, one can induce pulses from photographic flash- lamps, which is funneled uniformly onto the test structure. An infrared focal plane array camera, aimed and focused at the surface through an opening in the rear of the hand-held shroud, monitors the rapid cooling of the surface. The system operates by sending a heat pulse from the surface into the material, where it undergoes thermal wave reflection at either the rear surface or at any interior surface at which the thermal impedance changes, e.g., at disbonds, delaminations, etc. The effect of thermal wave reflections is to modify the local cooling rate of the surface. The cooling rate, in turn, is monitored through its effect on the infrared radiation from the surface, which is detected by the camera, and processed as a sequence of images by the control computer. The contrast in the processed images reveals the presence of defects in the interior or variations in the thickness of the material. In Figure 12, a Thermal Wave Image example is shown for corrosion and unbond near a tear strap/stringer of a Boeing 737

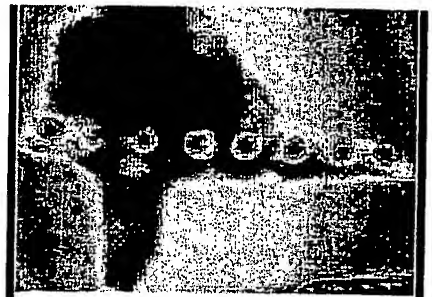


Fig 12: Thermal Wave Image of Corrosion and Disbonding near tear strap/stringer of a Boeing 737

Conclusion

As we begin the third Millennium it is interesting to look back and see how far the field of NDE was advanced and what are still the challenges. Across the board, all the exiting NDE methods were benefited from enormous improvement and emergence of new techniques. Considering the fact that each of the methods is constrained by certain limitations, efforts are increasingly being made to integrate several methods to form multi-mode systems. Thus, the complementary capabilities offer increased functionality and the overlapping capabilities improve the reliability. Advancement in miniature electronics, actuators, robotics, wireless communication as well as sensors are expected to make great impact on the field of NDE in the coming years. The effect of flaws on the wave response is analyzed using theoretical models and analytical tools, including finite element techniques. Inversion techniques were developed to extract flaw characteristics and material properties using nondestructive measurements. The developed analytical capabilities and computer graphics allow interactive simulation of the behavior of the wave and to develop inspection procedures in cyberspace.

The search for smarter methods that can rapidly and inexpensively detect very small flaws in complex materials and structures, at very high probability and repeatability, will continue to be a challenge for NDE. Efforts will be made to further reduce the complexity associated with inspection procedures, where redundant tasks will be performed by computers leaving the role of human operators to making critical decisions. It is difficult to predict when, global standards will eventually be accepted worldwide and cover all NDE standards, inspection procedures and personnel training/qualifications. However, this globalization trend will continue to grow to cover all countries.

Acknowledgement

The research at Jet Propulsion Laboratory (JPL), California Institute of Technology, was carried out under a contract with National Aeronautics Space Agency (NASA).

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Ultrasonics

Ultrasonics is one of the most versatile and informative NDE methods and [Bar-Cohen, 1990]. The various modes that these waves can support allow the extractions of detailed information about flaws as well as determining various material properties. Techniques were developed employing the various wave modes as well as scattering and mode-conversion that are associate with the wave interaction. Examples of such techniques include the Acousto-Ultrasonics, which is practically used for flaw screening, and the ultrasonic angular insonification to induce the polar backscattering and leaky Lamb waves. Also, to perform rapid inspection portable scanners were developed with some that can crawl on the surface of the test structures and conduct scanning. To simplify the imaging process without the use of mechanical scanning array transducers and CCD technology can now be used to form the ultrasonic equivalence of the video cameras. The difficulties associated with the need for liquid couplant, which mostly affects field application, led to the development of various fixtures including water filled boots and wheels, bubblers and squirters. Recently, a dripless bubbler was developed at Iowa State University where water is recycled using a vacuum pump [Patton and Hsu, 1998]. Even though the bubbler adds significant mass to the probe mount, it maintains most of the water and it was demonstrated as an effective method of performing the equivalent of immersion in field conditions. Alternative dry coupling methods were also developed including the use of air- coupled piezoelectric transducers, Electro-Magnetic Transducers (EMAT) and Laser Ultrasonics [Green, 1997].

Dry Coupling Techniques

The inability to transmit and receive ultrasonic waves through air or gas was a limiting factor in developing rapid field inspection, testing porous or water sensitive materials, and others. Most ultrasonic NDE applications operate at frequencies in the range of 1- 10 MHz, where traveling through air is highly attenuative. The acoustic impedance of air differs significantly from the one for the piezoelectric transmitter and the test part causing reflection of most of the energy. Therefore, only a very small fraction of the energy is transmitted through the part and back to the transducer.

Air-Coupled transducers

One solution to overcoming this air-coupling problem without using additional transition media has been the induction of sufficiently high sound level and using high-gain, low-noise amplification [Grandia & Fortunko, 1995]. To enhance the transmitted energy, the transducer is used with no backing layers and thus taking advantage of the high mechanical-quality factor Q of piezoelectric disks. To improve the generation and reception efficiencies of the transducer, its front protection layer is made of a thin porous material having low specific impedance. The transducer is driven by tone-bursts with a center frequency that exactly matches its thickness- mode resonance and using focused transducers further increases the sound pressure. Such transducer and hardware modifications allowed the operation of air-coupled ultrasonic C-scans at frequencies in the low Megahertz range.

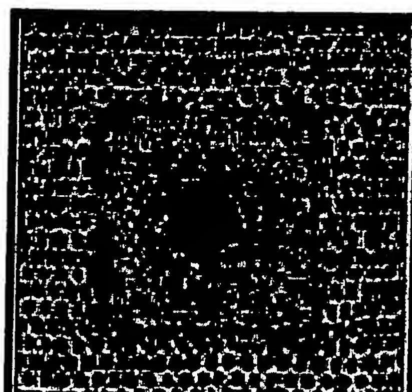


Fig 8: A 400 KHz air-coupled through-transmission C- scan of solar honeycomb panel with a 5x5-cm stiffener insert

While it is still limited to materials with relatively low acoustic impedance, such as composites,

it is already being used extensively for applications where water can not be used as a couplant. In Figure 8, an example of a C-scan is shown where a solar honeycomb panel with a 5x5-cm stiffener insert was tested using a 400 KHz air-coupled through-transmission. The bonded honeycomb core, the area of the insert and the missing core can be easily seen.

Electromagnetic acoustic transducer (EMAT)

EMAT is a transducer that uses eddy current to generate and receive acoustic signals that operates without a coupling medium [Oursler & Wagner, 1995]. The transducer can induce specific ultrasonic modes including normal beam and angle-beam shear wave, Shear Horizontal (SH) plate wave, Rayleigh wave and Lamb wave. The ability to induce horizontally polarized shear waves has a great significance for the inspection of austenitic welds. Another advantage of EMAT is the ability to operate at high temperatures. The main disadvantage of EMAT arises from its relatively low transmitted ultrasonic energy causing electronic noise to constrain its dynamic range. Also, the induced energy is critically dependent of the probe proximity to the test object, which for practical applications it is commonly maintained below 1-mm. Generally, EMAT transducers are used at frequencies below 2-4MHz.

Laser induced ultrasound

Laser ultrasonics is one of the effective methods of inducing and receiving ultrasonic waves without the need for couplant. The received signals are evaluated very similar to the pulse-echo technique and parts can easily be scanned from a distance of about 3-4 meters. The method induces short pulses in the range of 10-μsec causing a rapid heating and expansion of the surface forming elastic pulses. The reflected signals are examined by interferometry and such systems were developed by several research organization including the Center for NDE at John Hopkins University, Hughes Research Lab and the Canadian National Research Council [e.g., Monchalin, et al, 1998]. Also, a commercial system was developed by UltraOptec (Québec, Canada), who delivered one of its products to the Air Force maintenance facility at McClellan Air Force Base for inspection of composite and bonded structures [Fiedler, et al, 1997]. The method is effective for inspection of structures with complex geometry allowing examination of surfaces with a slope of up to about ±45^{o} . This allows mapping defects in parts that are contoured and presenting the results in 3-D (see Figure 9) with is no critical orientations requirement for the incident beam. The limiting factor in the scanning speed is the inability to induce pulses at high rate, where an average of 100 pulses/sec is commonly used. Overall, the cost and the sensitivity of the laser ultrasonic technique are limiting the wide usage of laser-ultrasonics. New techniques are continuously being introduced in an effort to reduce the cost of the hardware. However, the sensitivity is fundamentally limited to about 45dB because there is a lower bound on the sensitivity of detecting a single phonon, whereas the upper limit is set by thermal damage prevention. Commercially available systems are offering user friendly imaging software, which displays A-scans, B-scans and C-scans, as well as 3-D ultrasonic images that can be easily manipulated for various angles of view.

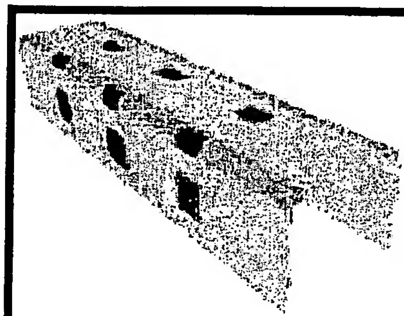
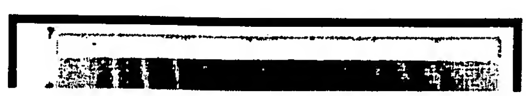


Fig 9: A 3-D C-scan image of a curved part with flaws at various depth (identified in colors) using laser-ultrasonic time-of-flight

Oblique Insonification NDE of Composites

Composite materials are now making a significant percentage of aircraft and spacecraft flaw critical



structures. These materials susceptibility to flaws during production and assembly as well as the cost associated with their inspection are hampering their wide use. These materials are now reaching service duration for which flaws due to aging are requiring a greater attention. Standard NDE methods developed to inspect metallic structures were adapted by the industry for inspection of composites partially accounting for their multi-layered anisotropic nature. The adapted methods are providing limited and mostly qualitative information about the material properties and defects. The author discovery of the ultrasonic Polar Back-Scattering (PBS) [Bar-Cohen & Crane, 1982] and the leaky Lamb wave (LLW) [Bar-Cohen & Chimenti, 1994] phenomena (1979 and 1982, respectively) in composites added a powerful arsenal of quantitative NDE methods. These phenomena are based on obliquely insonified ultrasonic waves and the numerous analytical and experimental studies followed the discovery of these phenomena are helping to pave the way for their practical application. Using PBS, the fiber orientations can be determined and porosity clusters as well as fatigue cracks can be mapped. Further, using inversion of LLW data, the elastic properties of composite panels can be determined, flaws can be characterized uniquely, and the quality of adhesive bonded-joints can be determined [Bar-Cohen, et al, 1993 and Bar-Cohen & Lih 2000]. The LLW data is acquired in the form of dispersion curves that show the phase velocity as a function of the frequency along various polar angles with the fibers. To harness the capabilities that are offered by LLW and PBS, a computer-controlled scanner was developed jointly with QMI (Costa Mesa, CA) as a C-scan attachment. Recent modifications of the data acquisition capability increased the speed of acquiring dispersion curves to fractions of a minute. Rapid acquisition of dispersion curves is very important for the practical implementation of quantitative mapping of the material properties. In addition a new capability was introduced using frequency modulation allowing to record very low amplitude LLW modes as shown in Figure 10.

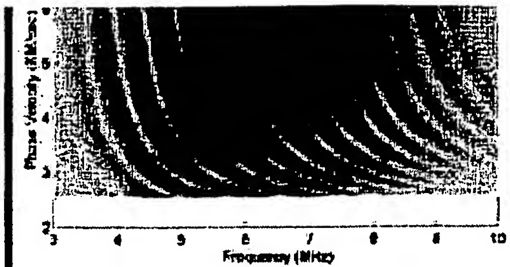


Fig 10: A new method of acquiring dispersion data, developed at JPL, allows recording very low amplitude modes

Portable Real-Time Imager Using CCD

Ultrasonic imaging using a portable real time system that employs 2-D sensing array has been shown to be effective field inspection tool [Lasser & Harrison, 1997]. An ultrasonic camera displays images at TV frame rates and this capability contrasts the conventional C-scan, which generates image by point-by-point scanning of test areas. This real-time imager offers a portable, practical tool for rapid visualization of flaws using an integrated circuit, which converts ultrasound data to standard TV output. The system operates as a pulse-echo tester and it is designed to display different depth views by examining various time-of-flight ranges. The inspector applies an ultrasonic couplant over the desired test area and then presses the imager against the target insonifying it ultrasonic waves. The pulse-echo image appears on a small LCD screen mounted on the back of the probe. Controls are located on the handle facing the user and real-time adjustments can be made to select the desired characteristics of the image.